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DIRECT DRIVE WITH HIGH MOTION PERFORMANCE

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ABSTRACT

A direct drive on the basis of permanent magnet synchronous motor (PMSM) is considered and the method to improve its classical cascaded control structure is represented. The calibrated control strategy described in this paper takes into account the nonlinearities of the space vector PWM-inverter (SVPWM-inverter) and disturbances due to electromagnetic and cogging component of rotating torque. The proposed calibrated control improves the quality of 3-phase currents of PMSM, eliminates the harmonics of the electromagnetic and cogging torque and consequently improves the motion characteristics of the direct drive.

Index Terms – Direct drive, current control, torque ripples, brushless AC motor, inverter nonlinearities, PMSM, velocity ripples.

1. INTRODUCTION

Digital direct drives with permanent magnet synchronous motors (PMSM) are widely used in modern technologies. The elimination of mechanical gear improves the dynamic and static motion performances. The most useful control strategy of direct drives for position systems is the cascaded control structure. However, for high precision movement the use of cascaded structure is not always enough. To achieve high dynamic stiffness, high quality and bandwidth of torque and rotation smoothness, it is necessary to correct the nonlinearities and internal disturbances of the drive that can not be made using classical structure. In this paper the two sources of nonlinearities are considered. The first is the nonlinearity of IGBT-based inverter. The control algorithms of the inverter mostly are based on the assumption, that output characteristic of the inverter has a linear form. However, the practical application shows the difference between reference and output voltage of the inverter. The error of the output voltage is due to so called «dead time effect», which is inserted to prevent the phase shortage of inverter arms. Moreover, non-ideality of switching devices, such as on-state voltage drop, causes the error in the output voltage of the inverter and negatively influences on the quality of the current and torque control of the motor. In [4] and [7], several methods for voltage error compensation were presented. However, these methods are based on the complicated mathematical calculations and need complicated software. The section 3 of this paper presents a simple method of the inverter calibration to reduce the current distortion of the PMSM. The method is based on the «off-line» linearization of the inverter output characteristic, using an experimental measurement result of the PWM inverter voltage error.

The second nonlinearity to compensate is an internal disturbance of the drive provided by presence of torque ripples of PMSM. The torque ripples can be reduced by using program compensation in torque reference, which is described in section 4. In section 5 the experimental results of calibrated current control and torque ripples reduction using calibration table are presented. Section 6 contains the conclusion to this paper.

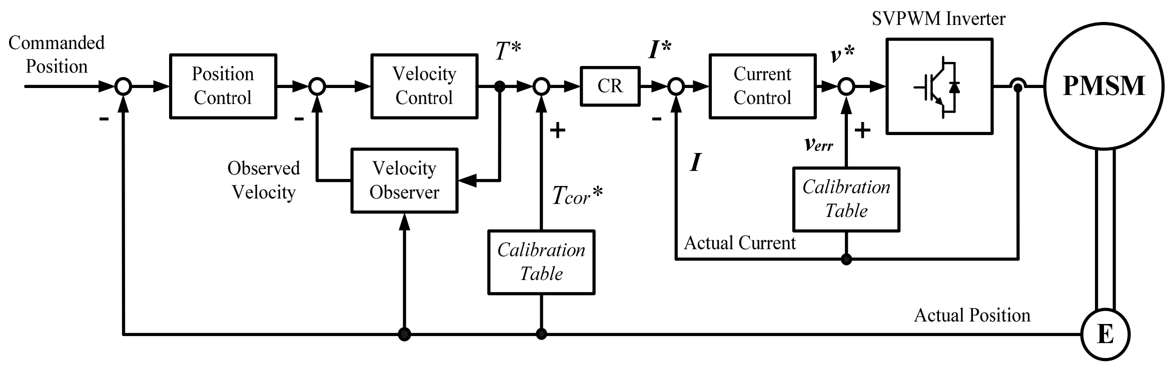


Fig. 1. Cascaded control structure of direct drive using calibration tables.

2. CALIBRATED CONTROL OF DIRECT DRIVE

The control structure of direct drive system consists of three cascaded control loops. To control the current, the digital PI-controller with ant-windup circuits is implemented. The output of PI-controller is the PWM-command of the inverter ***v****. In this work the space vector modulation of the inverter voltage is realized. The current control loop becomes the references of current from ***Current Reference*** block (CR) in rotor reference frame, considering that the controlled PMSM is the non-silent pole synchronous motor:

$$I^*_d = 0\,;\; I^*_q = T^* / \left(\frac{m}{2} K_T\right), \qquad (1)$$

where K_T is the torque constant of the motor, m – number of phases.

The torque reference T^* is the output of the velocity control loop, which also uses a PI-controller to hold on the commanded velocity on its reference value. The velocity feedback is designed with the help of velocity observer, which is described in [8]. The position control is realized by P-controller, which can become the commanded movement from function generator or trajectory generator of the CNC-system.

The main difference of the considering system from commonly used cascaded control structures is the using of the calibration tables to compensate the non-linearities of the direct drive. The calibrated control structure uses the calibration table in current control loop to compensate the non-linear characteristic of the SVPW-inverter and the calibration table to reduce the internal disturbances due to ripples of the rotating torque of the PMSM.

3. CALIBRATED CURRENT CONTROL

3.1. Measurement of the inverter voltage error

The determination of an inverter voltage error can be made with the help of current regulator, which becomes the quasi-constant references of current according to (2). In synchronous mode the motor will be in standstill and one of the phase currents should be equivalent to reference. In this case the current regulator should generate a normalized voltage according to the ideal characteristic of the inverter (3). However, the output of the regulator shows the difference between the real reference voltage of the inverter and the ideal reference. This error can be considered as an inverter voltage error, which regulator has to compensate to hold the actual current on its reference value.

$$I^*_d = I^*_{ref}\,,\; I^*_q = 0\,; \qquad (2)$$

$$v^*_{ideal} = (I^*_{ref}\;R) / \left(\frac{2}{3} U_{DC}\right); \qquad (3)$$

$$v_{err.} = v^* - v^*_{ideal}\,. \qquad (4)$$

It is well khown that voltage error is provided by time delays, which are inserted in control signals of transistors of the inverter, to eliminate the possibility of short circuit in one leg of the inverter, so called «dead time». The on-state voltage drop and turn on/off time of switching devises can also insert a distortion in output voltage of the inverter. In [3] it is shown that inverter phase voltage error depends on total delay from «dead time» and turn on/off time, sample time of control system, DC-voltage of the inverter and the sign of phase current (see Fig. 2):

$$U_{a.err} = \frac{T_{a.err}}{T_S} U_{DC} = U_{err.}\,\mathrm{sgn}(i_a)\,; \qquad (5)$$

$$U_{b.err} = \frac{T_{b.err}}{T_S} U_{DC} = U_{err.}\,\mathrm{sgn}(i_b)\,; \qquad (6)$$

$$U_{c.err} = \frac{T_{c.err}}{T_S} U_{DC} = U_{err.}\,\mathrm{sgn}(i_c)\,; \qquad (7)$$

$$\mathrm{sgn}(i) = \begin{cases} 1, & if \quad i > 0\,, \\ -1, & if \quad i < 0. \end{cases} \qquad (8)$$

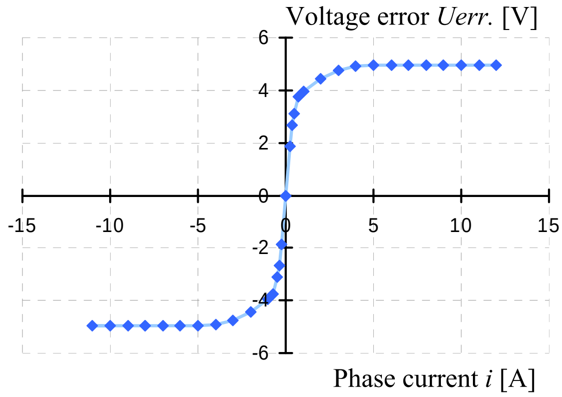


Fig. 2. Voltage error of the one phase of the SVPWM-inverter.

3.2. Compensation of the voltage error

The principle of the off-line voltage error correction (calibration) is shown in Fig. 3. The calibration table contains the measured and sampled values of the voltage error (Fig. 2) in normalized form as a function of phase current. The values of the calibration table are transformed into *dq* coordinates [3] and added to the reference voltage to compensate the nonlinearity of the PWM-inverter characteristic. It is also necessary to detect the sign of the current to consider the variation of the sign of the voltage error at the zero crossings of the current.

$$v_{d.C} = v^*_d + v^*_{d.err}\,; \qquad (9)$$

$$v_{q.C} = v^*_q + v^*_{q.err}\,. \qquad (10)$$

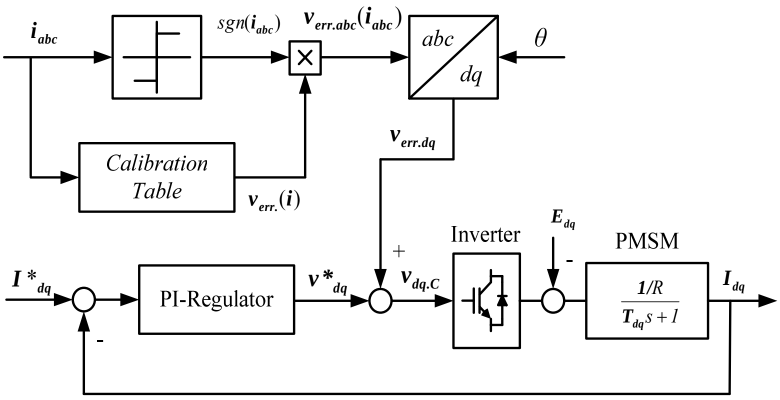


Fig. 3.Structure of calibrated current control.

4. TORQUE RIPPLES CORRECTION

The torque ripples have a large influence on the motion performance of PMSM. These ripples have the electromagnetic component, which depends on stator reluctance and harmonics of rotor magnetizing force and the cogging component from the permanent magnets of the motor. The torque ripples can be indirectly estimated in closed velocity loop system during one turn of motor at small speed range and no-load conditions (Fig. 4). In this experiment, the velocity regulator will generate the torque reference (Fig. 5) to overcome the cogging force and Coulomb friction of motor and hold the observed velocity near to the commanded value. The torque reference and corresponded position signal are saved as a table function $T^*_{cor}(\theta)$ in the system flash-memory and implemented as a program correction according to Fig. 1. The simple equation describes the proposed method:

$$T^*(k) = T^*(k) + T^*_{cor}(\theta)\,, \qquad (11)$$

where

$T(k)$ - the discretizated torque reference,

T^*_{cor} - the components of calibration table, addressed to position angle.

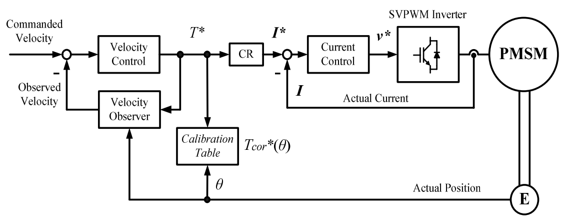


Fig. 4. Torque ripples estimation.

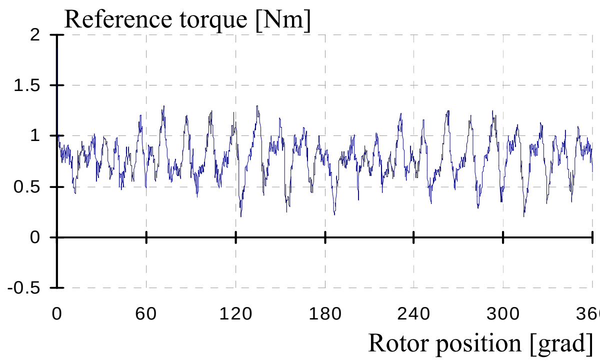


Fig. 5. Estimated torque ripples of the PMSM during one turn at commanded speed 1 rev/min.

The estimated torque reference has a constant component, that is the Coulomb friction torque and variable component, which can be analyzed with FFT. The FFT (Fig. 6) shows the presence of harmonics from cogging torque N=22, its component N=44, the component from stator teeth N=24 and distortion from phase currents N=11, which have non-ideal sinusoidal form.

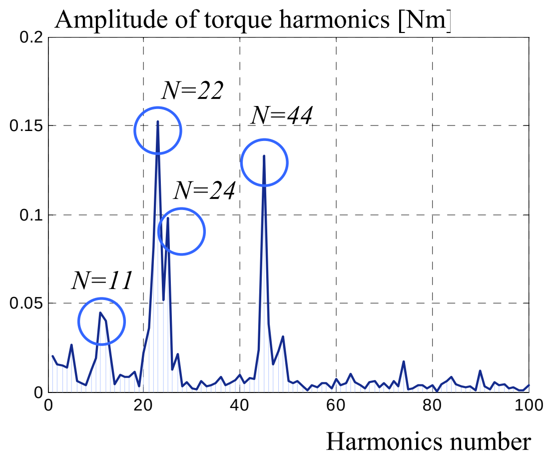


Fig. 6. FFT of estimated torque ripples.

5. EXPERIMENTAL RESULTS

The proposed calibration methods are realized using a DSP-based control system of the PMSM. The processor is the fixed-point DSP (TMS320F2812) with a clock frequency 150 MHz. Two Hall-effect current sensors are used to measure the phase currents of PMSM. An analog optical incremental encoder with 16200 lines/rev is employed to obtain the position information of the rotor. The sampling time of the current loop is 67 µsec and the sampling time of the velocity and position loops is 134 µsec. The 22-pole PMSM is used for the test. The other specifications of experimental system and test motor are shown in tables 1 and 2, respectively.

TABLE 1
SPECIFICATIONS OF EXPERIMENTAL SYSTEM

DC link voltage	310 [V]	AC supply	3x220 [V]
Dead-time	1 [µsec]	Switching device	IGBT
Sampling period of current loop	67 [µsec]	Sampling period of velocity and position loops	134 [µsec]

TABLE 2
SPECIFICATIONS OF TEST MOTOR

Motor type	PMSM	Stator inductance	15 [mH]
Continuous current	3 [Aeff]	Maximal speed	700[rpm]
Continuous torque	20 [Nm]	Number of poles	22
Stator resistance	3.2[Ohm]	Number of stator teeth	24
Number of phases	3	Position sensor: analog encoder	16200[ln./rev]

5.1. Results of inverter voltage error correction

To prove the efficiency of proposed calibration method of the current loop, the influence of two ranges of dead-time delays was analyzed and corrected in this work. Fig. 7-10 show the experimental results of calibrated current control for dead time 1 µsec and 3.2 µsec, where q and d current references are given as 0 A and 2.5 A for synchronous mode, respectively, and the motor operates at 100 rpm. The FFT with harmonics number identification for q-axis current was implemented to verify the calibration algorithm. For phase current analysis the THD is used, which is defined as:

$$THD = \sqrt{\frac{\sum_{n=2}^{20} A^2{}_n}{A^2{}_1}},$$

where A_1 and A_n are the fundamental component and n-th order harmonic component of the phase current, respectively.

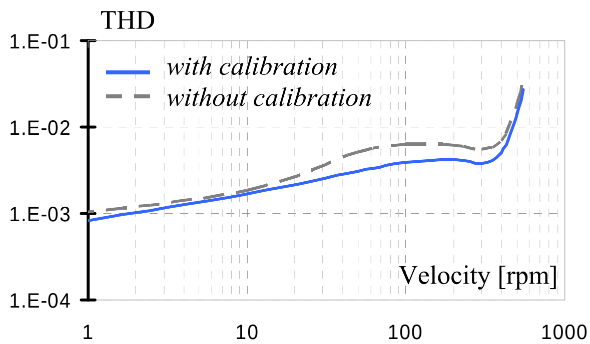


Fig. 7. Total harmonic distortion of phase current with and without calibration.

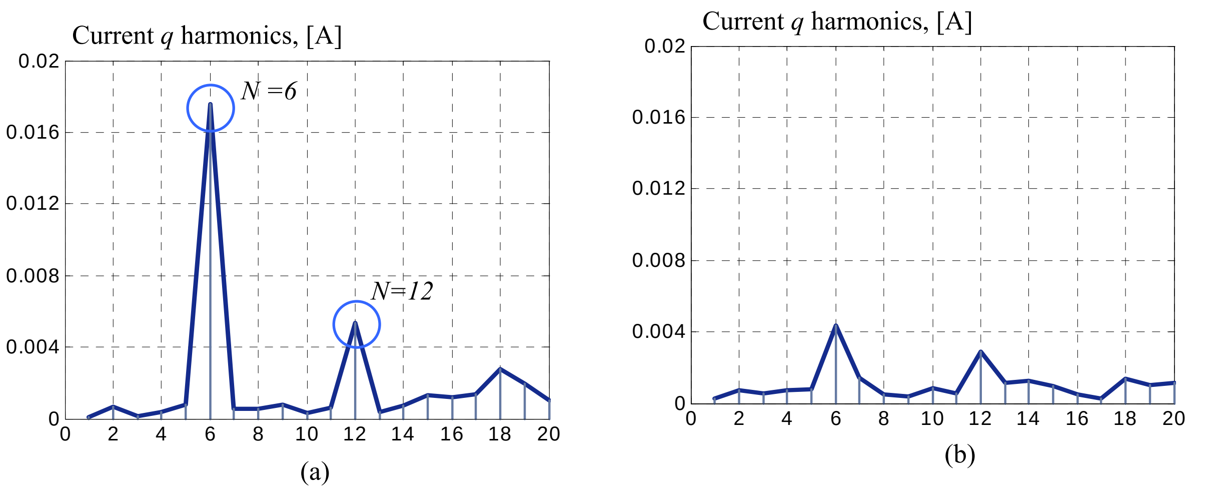


Fig. 8. FFT analysis of q current without (a) and with calibration (b) (dead-time 1 µsec).

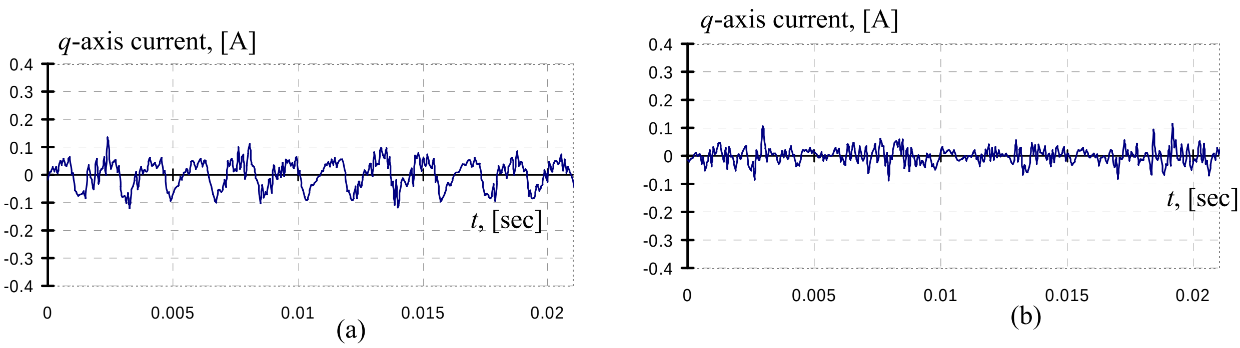


Fig. 9. Current q without (a) and with calibration (b) (dead-time 3.2 µsec).

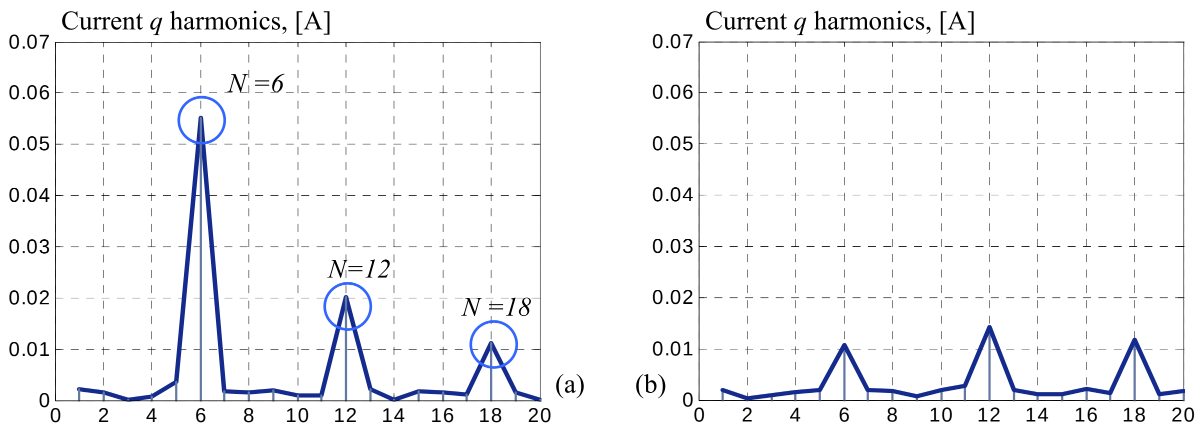


Fig .10. FFT analysis of q current without (a) and with calibration (b) (dead-time 3.2 µsec)

5.2. Results of torque ripples correction

The experiment of torque correction was carried out at low speed range 4 rpm and shows the reduction of cogging and Coulomb friction component of rotating torque of PMSM. In this experiment, the pulsations of electromagnetic torque were also compensated (Fig. 11). Fig 12 shows the effect of calibration method on torque reference (without of taking into account the Coulomb friction component) and pulsations of the observed velocity, which can be calculated as a difference between commanded and observed velocity. In Fig. 13, the FFT of calibrated torque and harmonics of velocity ripples before and after calibration are introduced.

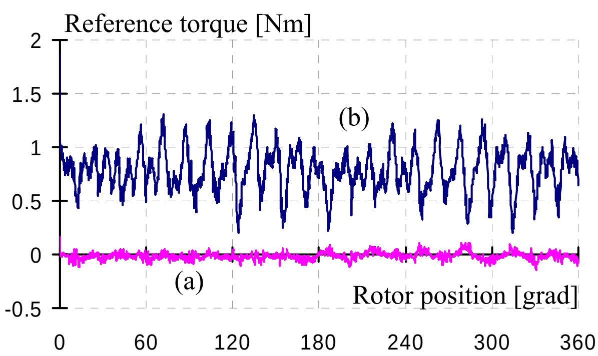


Fig. 11. Torque reference with (a) and without calibration (b).

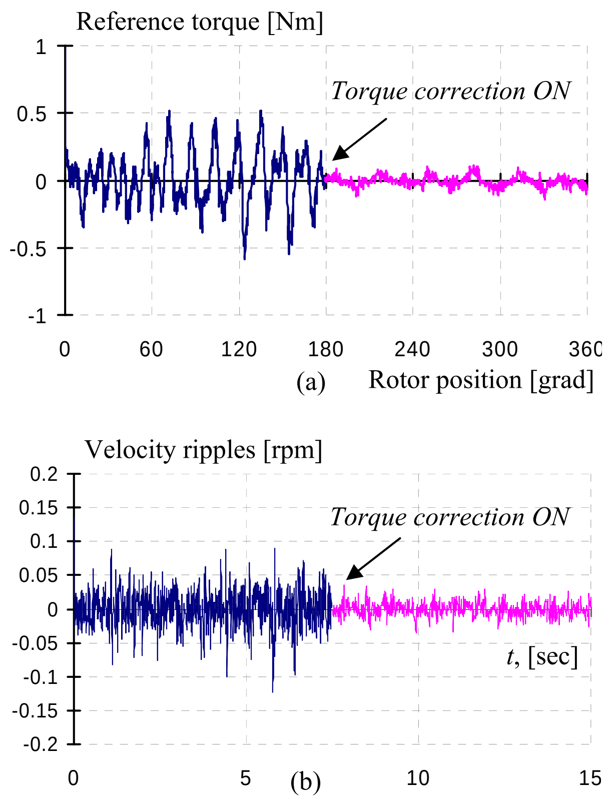
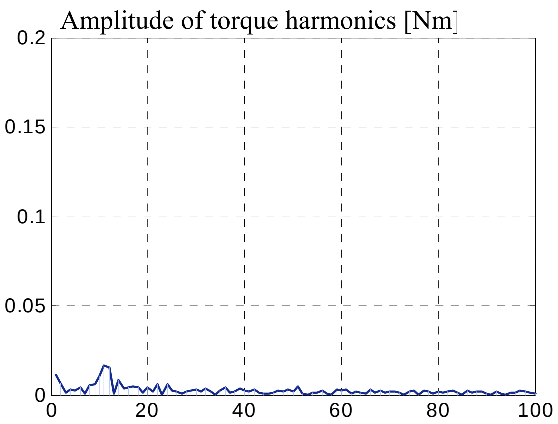
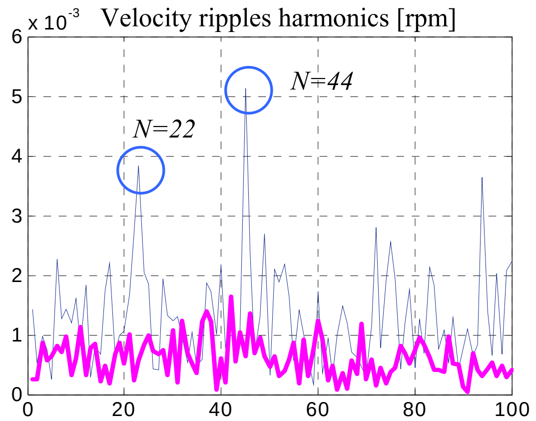


Fig. 12.Effect of calibration method on torque reference (a) and velocity ripples (b).



(a)



(b)

Fig. 13. FFT of torque reference with correction (a) and velocity ripples with and without correction (b).

6. CONCLUSION

The simple «off-line» method of the inverter non-linearity correction is proposed. This method is based on off-line measurement of the inverter voltage error provided by the «dead-time» delay and the on-state voltage drop of the switching devices. The results of calibrated current control show the good correction of the inverter voltage error, that affects positive on actual current and reduce the typical current harmonics from «dead-time» distortion [10]. The method of torque ripples correction of the PMSM was also presented in this paper. The calibration takes into account the distortions of the rotating torque of the motor due to cogging component, Coulomb friction and electromagnetic pulsations. The presented calibrated control allows to achieve the high quality of current, and consequently torque control and reduce the velocity pulsations by correcting the torque ripples of the PMSM. The experimental results show the better motion performances at low speed ranges and verify the validity of proposed control method.

7. REFERENCES

[1] Lothar Springob. Synchron-Servoantrieb mit hoher Rundlaufgüte und Selbstinbetriebnahmefunktion/ Lothar Springob.-Aachen: Mainz, 1995. Wuppertal Univ., Diss., 1994.

[2] Frank Herty. Korrektur von totzeitbedingten Störungen in elektrischen Antrieben mit Pulsewechselrichtern. (Diss. Univ. Kaiserslautern), Shaker Verlag, Aachen 2002.

[3] Hyun-Soo Kim, Hyung-Tae Moon, Myung-Joong Youn. On-line dead-time compensation method using disturbance observer. IEEE transactions on power electronics, Vol. 18, No. 6

[4] Peter Weichbold, Thomas von Raumer. Influence of dead time effects of PWM-VSI on current control. EPE 2001-Graz.

[5] Raymond B. Sepe, Jaffrey H. Lang. Inverter nonlinearities and discrete-time vector current control. IEEE transactions on industry applications, Vol. 30, No. 1, January/February 1994

[6] Heiko Schmirgel, Jens Onno Krah. Compensation of nonlinearities in IGBT power stage of servo amplifiers through feed forward control in the current loop. PCIM EUROPE 2005. Proceedings.

[7] Lazahr BEN-BRAHIM. New optimal methods for PWM inverter dead-time compensation. EPE 2001 - Graz.

[8] Digital Control Applications with the TMS320 Family. Selected Application Notes. 1991.

[9] Толстых О. А. Автоматическая настройка цифрового ПИ-регулятора тока вентильного двигателя. Труды МЭИ. Вып. 684.-М.: Издательский дом МЭИ, 2009.-66с.

[10] Analog Devices. Motion Control. Training and Seminars. Copyright 1995-1999. Analog devices Inc.